A PRACTICAL APPROACH TO CRYSTAL OSCILLATOR CIRCUITS IN DETERMINING LOAD CAPACITANCE

GENERAL

The following discussion of oscillator circuits uses a rule-of-thumb approach with a touch on the theory. Basically, an oscillator is an amplifier with gain greater than unity, and a network feeding a portion of the output back to the input in the proper phase. The feedback network may be LC, RC, or for more precise control, a quartz crystal. In a single stage oscillator the feedback voltage requires a 180 degree phase shift (assuming 180 degree shift in the amplifier) before introduction into the input terminals. In a two stage oscillator this phase shift occurs in the second stage, therefore an in-phase feedback is used. Stated another way, the loop phase rotation, in the voltage, must equal zero or some integral multiple of 360 degrees.

The feedback level controls the power through the network and thus the power dissipated in the network. This is an important consideration when using quartz crystals.

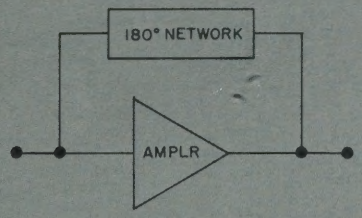


FIGURE 1

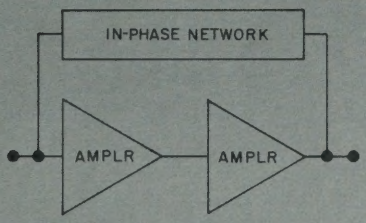


FIGURE 2

THE QUARTZ CRYSTAL

The quartz crystal may be represented by an L, C, R circuit. (fig. 3) Co is capacitance formed by the crystal electrodes plus any holder capicitance. The L1, C1, R1 branch is called the "motional arm". The one element in this branch of practical interest is the "motional or series resistance" R1. At the frequency of mechanical resonance the reactances of L1 and C1 are equal and opposite. At this frequency the crystal appears to be a resistance R1 in parallel with Co. This is the "series resonant" (or "resonant") frequency. Above the series resonant frequency, the crystal appears as inductance L1 in parallel with Co. This combination forms a parallel resonant circuit and is the parallel resonant (or anti-resonant) frequency. The crystal appears as a low impedance at series resonance and a high impedance at parallel resonance. In an oscillator circuit the crystal operates between these two points. Series resonance is obtainable in a circuit. The anti or parallel resonant frequency, in practice is lower than the frequency considering only Co and L1. This is due to external capacitance in the oscillator circuit which appears across the crystal. It stands to reason that an oscillator circuit which does not present a stable load to the crystal will cause the resultant oscillator frequency to vary, not because of the crystal, but because of the circuit variations. "Antiresonant" (AR) is a less stable mode because of this. Light crystal loads should be avoided.

A typical crystal at 10 megahertz will have an inductance greater than 10 millihenries, requiring less than 1 pf for resonance. Therefore, small external variations in capacitance can cause considerable frequency shift.

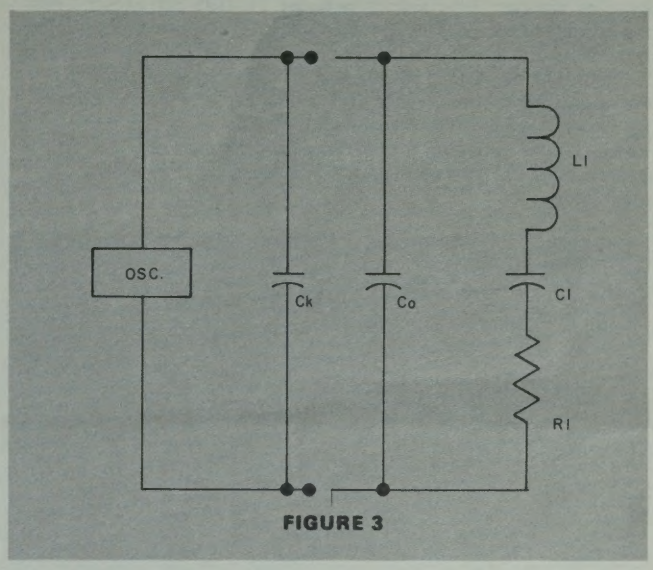


FIGURE 3

Referring to FIGURE 4, a generalization of inductive reactance X(L) and capacitive reactance X(C) is shown. On the left side of the chart dF represents the difference between series and anti-resonant frequencies. On the right side, Ct represents Ck circuit capacitance plus Co crystal capacitance. It is evident from this graph that as Ct approaches Co the slope of the curve increases. Drawing a horizontal line between the two curves at several equally spaced points shows that at low values of Ct greater dF changes occur.

In circuits operating fundamental type crystals, a good compromise between stability and trim range has been found using 32 pf. A more complete discussion of this can be found in later sections. During our rule-of-thumb discussion of load capacitances, the circuit capacitances and inductances which are small, compared to lump values, will be neglected.

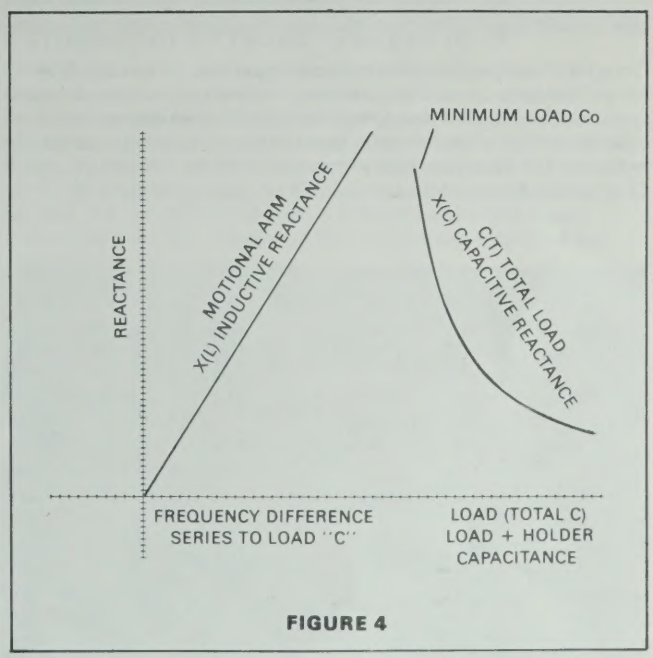


FIGURE 4

TYPES OF OSCILLATOR CIRCUITS

Circuits may be considered in two general types, based on the connection of the crystal.

Referring to FIGURE 5A, circuit A (Miller) connects the crystal between base and emitter (grid cathode). FIGURE 5B, circuit B has the crystal connected between base and collector (gridplate). Circuit A depends on capacitance Cbk (internal) for feedback. For oscillation to occur, the impedance of the collector circuit must be inductive. For approximation, the crystal load will be capacitance Cb. Cb will be circuit capacitance plus base-emitter capacitance. If circuit capacitance is zero, then 5 pf or 10 pf may be used as approximation of load capacitance depending on stray wiring capacitance.

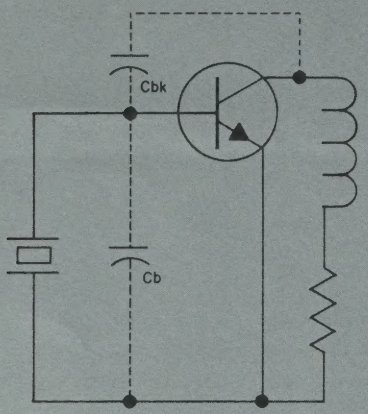


FIGURE 5A

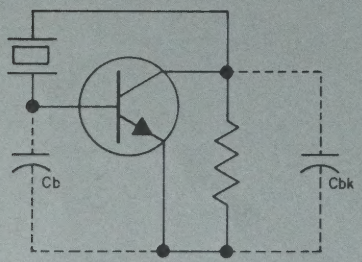


FIGURE 5B

Circuit B (Pierce) requires the collector impedance to be capacitive for oscillation to occur. The minimum load will be the collector-base capacitance in parallel with the combination of base-emitter and collector-emitter capacitances in series. As lump values are added to Cb and Ck, the crystal load will approximate the value of Cb and Ck in series. A modification of circuit B is shown in FIGURE 6.

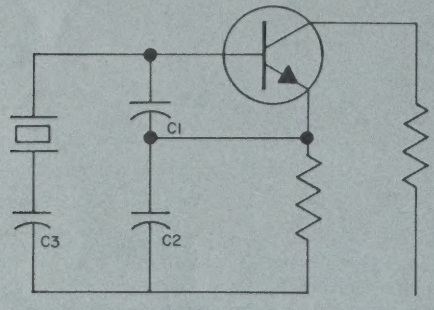


FIGURE 6

This circuit is widely used in present day communication equipment. The circuit is commonly called a modified Pierce or modified Colpitts. The crystal load is almost totally made of C1, C2, and C3 in series. Capacitors C1 and C2 may be quite large and swamp any instability reflected by the transistor capacitances. C3 may be variable for frequency trim purposes.

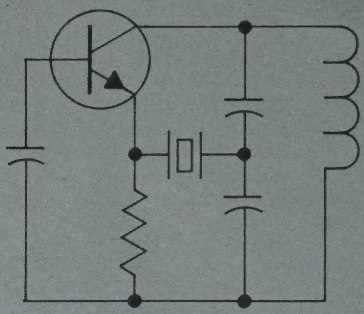


FIGURE 7

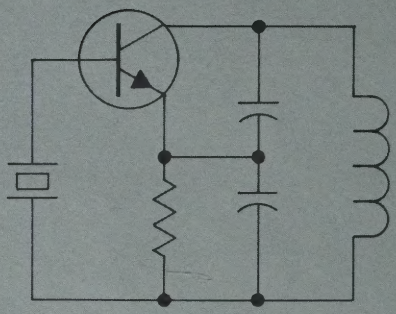


FIGURE 8

Figures 7 and 8 show two versions of the grounded base oscillator using crystals. Both circuits use crystals calibrated for series resonance.

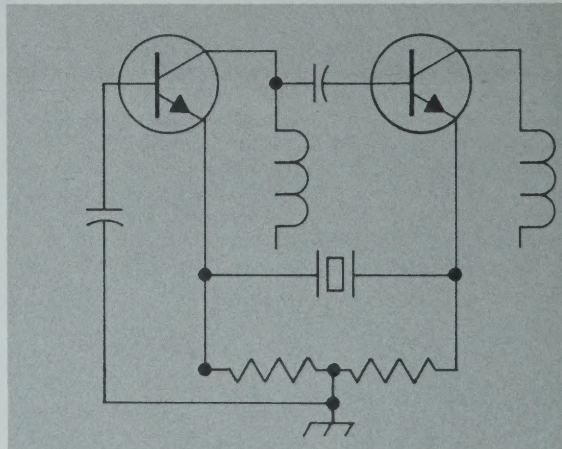


FIGURE 9

The circuit shown in FIGURE 9 is a transistor Butler type using two stages, and a crystal calibrated at series resonance.

The circuit in FIGURE 10 is of the type used in many crystal test oscillators. Series resonant conditions can be accurately produced with proper construction and tuning.

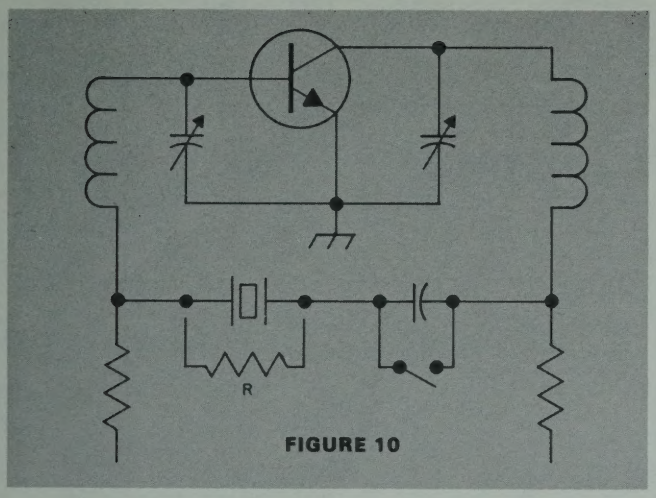


FIGURE 10

With capacitor C shorted and resistor R substituted for the crystal, the tuned circuits are adjusted to the same frequency and so the circuit self-oscillates at approximately the crystal frequency, the value of resistor R being approximately the series resistance of the crystal. With the crystal installed in place of R, the frequency of oscillation (C shorted) will be the series resonant frequency of the crystal. (We have neglected consideration of drive level and stray capacitances which must be considered for accurate results). With the short removed from C, the frequency of oscillations will be that of the crystal operating into load C.

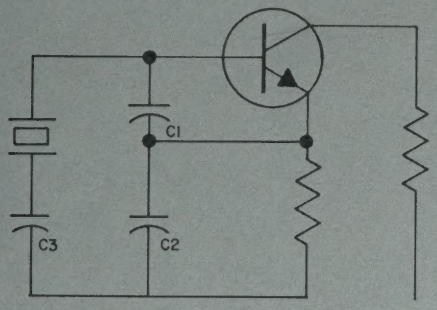


FIGURE 11A

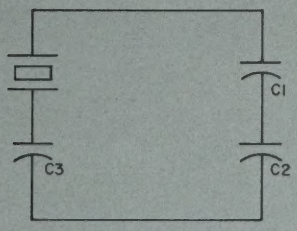


FIGURE 11B

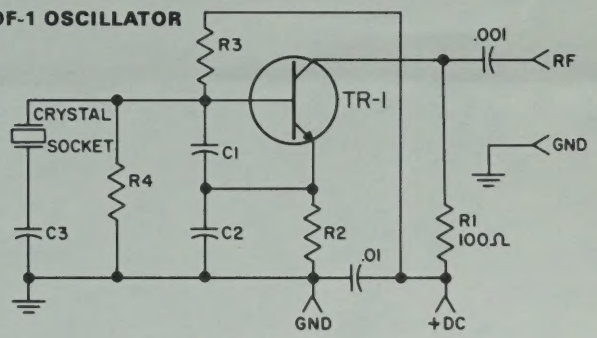
ESTIMATING LOAD CAPACITANCE

Let us examine a sample circuit to determine the load capacitance presented to the crystal.

FIGURE 11A shows the general circuit used in the International "OF" series. Phase shift is accomplished with the transistor and the feedback applied with RC components. The circuit operates from 1 MHZ to 66 MHZ using fundamental and third overtone crystals. Capacitor values are changed at various frequencies to maintain the proper phase shift and feedback. The phase shift, using a given set of capacitors, changes with frequency. Therefore within an operating range, the actual load capacitance presented to the crystal will change slightly from one end of the range to the other.

FIGURE 11B reduces the circuit to the components affecting the feedback and crystal load capacitance. The reactance of C2 at the crystal frequency must be less than R2 so that the voltage across C2 is substantially in phase with the voltage developed across R2. The voltage divider C1/C2 sets the feedback level. The load presented to the crystal will be the resultant reactance of C1, C2, and C3 in series. This capacitive reactance is opposed by the inductive reactance of the crystal. The crystal oscillating frequency will shift such that its CHANGE in inductive reactance cancels the reactance of C1, C2, and C3. The result is a series resonant circuit consisting of the crystal inductance, C1, C2, and C3. Using 220 pf for C1 and C2, and 30 pf for C3, we calculate a load capacitance of 23.6 pf. Using 470 pf for C1, and C2, and 30 pf for C3 we calculate a load capacitance of 26.6 pf.

OF-1 OSCILLATOR



OF-1
LO (FUND)

RANGE NO	FREQUENCY MHZ	R4	R2	R3	C1	C2	C3
2	2.0 to 15.0		680	47K	470	470	30
3	4.0 to 22.0		680	47K	220	220	30

OF-1
(3RD OVERTONE)

RANGE NO	FREQUENCY MHZ	R4	R2	R3	C1	C2	C3
4	18.0 to 28.0	2200	470	4700	220	47	
5	28.00 to 60.0	2200	470	4700	100	18	

ESTIMATING CRYSTAL "PULLABILITY"

FIGURE 12 may be used to estimate the difference between series resonant and parallel resonant frequencies. Since the total C(t) capacitance is made up of the circuit load and the holder-electrode capacitance C(o), the minimum capacitance is C(o) if Ck (circuit load) is zero. In FIGURE 12 the curves on the right represent four different pin to pin holder capacitances. The right scale is capacitance Ct (Ck plus Co). The left half of the scale is a factor used with the table to calculate the KHZ frequency difference between series and the circuit load used.

For example, determine the frequency difference between series and a 32 pf circuit load for a 10 MHZ fundamental crystal. Assume the holder C(o) is 6 pf. C(t) then equals 38 pf. Entering the C(t) scale at 38 pf, draw a line upward to intersect the pf holder curve. Proceed left with a horizontal line to intersect the factor curve, then straight down to the factor scale. The intersection is at a factor of 8. Referring to the table, multiply 8 × .03736 × 10, giving a frequency difference of 2.99 KHZ. To further determine the frequency difference between a 32 pf load and 15 pf load, a 15 pf load plus 6 pf holder gives 21 pf C(t). Following the same procedure, we determine a factor of 14.8, or a frequency change (series to 15 pf) of 5.53 KHZ. The change 32 pf to 15 pf would then be 5.53−2.99=2.54 KHZ. Using the same loads and holder, but an overtone crystal at 40 MHZ, we find a series to 32 pf frequency of 1.33 KHZ. The series to 15 pf frequency is 2.46 KHZ, or a 32 pf to 15 pf change of 1.13 KHZ.

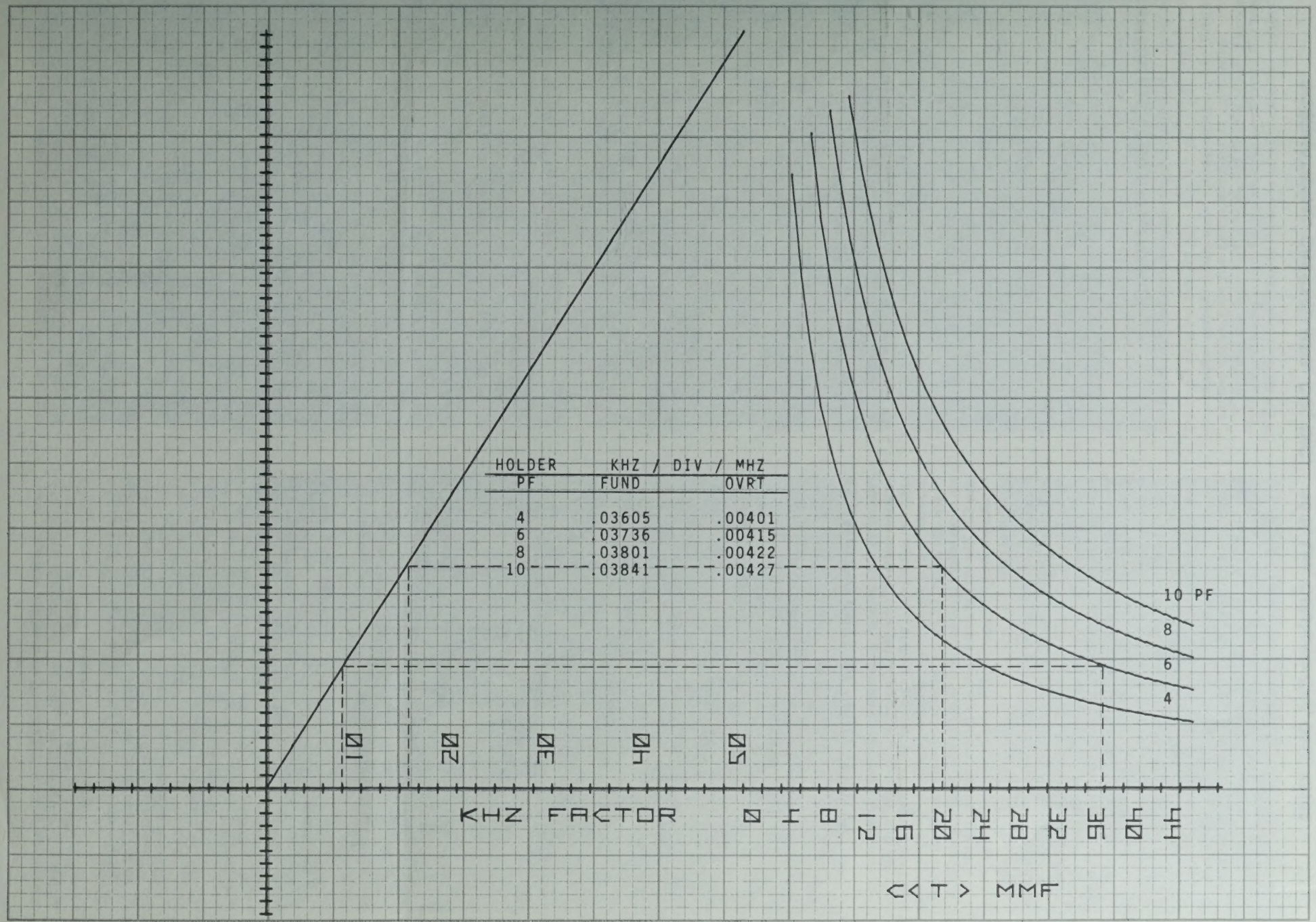

HOLDER
PF
KHZ / DIV / MHZ
FUND
OVRT
4 .03605 .00401
6 .03736 .00415
8 .03801 .00422
10 .03841 .00427
10 PF
8
6
4
01
02
03
04
05
KHZ FACTOR
0 4 8 12 16 20 24 28 32 36 40 44
<< T > MMF

FIGURE 12